

## **Surfzone Water Properties Sensor (SWAN)**

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### **LONG-TERM GOALS**

Our long-term goal is to develop a suite of compact, inexpensive in situ optical property sensors for use on autonomous platforms. As part of this long-term goal, our Phase I research efforts have focused on design, development, and testing of an inexpensive (nominally expendable) water property measurement system to provide environmental optical parameters in the surfzone that are critical for mine countermeasures operations. Work under the Phase I SBIR has been enabled by recent technological advances, including recent development of attenuation, scattering, and backscattering sensors for AUVs and other compact platforms. A SWAN (Surfzone Water Attenuation Node) will have a newly designed sensor (the BAM3) measuring multi-spectral attenuation,  $c$ , at 470, 532, and 660 nm, as well as GPS and RF communications. SWANs will be able to operate as drifters or as moored packages and will be capable of intelligent networking.

In Phase-II, a SWAN-x version will also be developed that will additionally have recently developed sensors measuring total scattering (AUV-B) and multi-wavelength backscattering (ECO-BB3). As a comprehensive but compact package measuring attenuation, scattering, absorption, and backscattering, with an expected product cost of \$10-15K, the SWAN-x is expected to also have commercial potential in the environmental research and monitoring markets. For Naval surfzone operations, it is envisioned that several networked SWANs could be deployed parallel to shore along with a SWAN-x providing more comprehensive optical information. Measured optical properties have direct application in constraining performance prediction models for optical MCM applications including passive hyperspectral imaging, active lidar detection, and diver visibility.

### **OBJECTIVES**

The overall objective is to develop an inherently scalable solution for determining optical properties important for surfzone mine-countermeasures (MCM) and basic research at a reasonable cost. For Phase-I of the project, the objective was to demonstrate the feasibility of our approach for measuring multi-spectral beam attenuation with a compact, inexpensive sensor. The key innovation is making a good quality measurement at low cost. Our objectives for Phase-II include fabrication of complete SWAN systems and testing multiple networked nodes in surf zone environments.

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## APPROACH

Optically based methods for Mine Counter Measures (MCM) include passive detection with hyperspectral imaging spectrometers, active detection with lidar platforms, and direct human diver sighting. Environmental optical conditions reconnaissance before deployment of these assets can be used to predict and optimize asset performance. For active systems, performance prediction usually involves estimating a Probability of Detection (PD) or Probability of Identification (PID) as a function of operational parameters such as platform towing altitude above the bottom. Performance optimization for these assets could range from adjusting operational parameters to optimize chances of detection to helping determine the most effective asset for a given set of conditions or making the determination that any asset deployment would be ineffective.

In the surfzone (< 3 m depth to the shoreline), passive detection methods have advantages because towed platforms often are not practical in very shallow water and low flying assets such as helicopters towing close to shore may be exposed to enemy fire. Hyperspectral imagers may be flown at safer altitudes using Unmanned Aerial Vehicle (UAV) drones. Deployment of divers is undesirable for such high risk operations. Since active lidar systems and divers may nonetheless have roles in surfzone MCM in some circumstances now and in the future, these methods are also considered.

For 1) predicting the depth to which we may “see” the bottom and differentiate contrast between different bottom types in passive imaging applications, 2) constraining parameters in lidar applications, and 3) predicting diver visibility, the optical parameter of critical importance is beam attenuation, *c*. As such, a focus of this project is developing an attenuation device suited for surfzone deployment on a compact platform. Design criteria for this sensor include low cost (<\$2K), low power, compact, and multi-spectral resolution. The sensor will be incorporated into a robust deployment package called a Surfzone Water Attenuation Node (SWAN), which will include GPS and wireless communications with networking capabilities.

An illustration of the optical layout for the beam attenuation meter, termed the BAM, is shown in **Fig. 1**. Using reflective prisms to fold the optics allows for a compact design while maintaining linearity and resolution using our standard LED's and ECO based detection circuitry. The optical layout of the BAM-triad is shown in **Fig. 2**. Collimated light paths from 3 LED sources passes through an dichroic prism called an X-Cube. BAM-Triad does not use the X-Cube for color combination necessarily but for optical path simplification. At the output of the X-Cube, the light passes through a 50/50 non-polarizing beam splitter (NBS). One-half of the light is directed to a reference detector. The reference detector is used to correct the measurement signal for temperature effects both in the LEDs' outputs and the main detector's response. With half of the light at the output of the NBS, it passes through the 5cm test length. Finally, the remaining light that has not been attenuated within the test volume is passed through a plano-convex lens (10 mm in diameter) with a focal length of 36 mm. The light passes through a 6 mm OD aperture, and is focused on a 1.5 mm OD aperture. Behind the 1.5 mm OD aperture is the signal detector. The optical, electronic, and mechanical components are cheap, and the design would lend itself to snap-together assembly. The BAM would be suitable for incorporation into a variety of platforms for sampling the surf zone and other aquatic environments.

Phase I implementation of our concept involved fabricating and testing a bench top version of the BAM. The BAM-Triad was developed and bench tested during the Phase I Option. Relative errors in measuring attenuation with this sensor are being assessed and directly related to resulting errors expected in image interpretations in the surf zone such as visibility, depth penetration and seafloor property characterization. Phase-I work also included comprehensive designs and specifications for

surf zone drifter designs. In future Phase-II work, 3 SWANs and 1 SWAN-x will be fabricated and tested as an integrated surfzone sampling network.

## WORK COMPLETED

The Phase-I Option was carried out in the beginning of FY08, with a Final Report submitted in April 2008. Phase-I Option work focused on the BAM-Triad development, specifically:

- Bench testing the BAM optical design characterizing the temperature compensation and response linearity.
- Assembling and bench testing the 3 wavelength (470, 532, and 660nm) BAM (termed BAM-Triad in this document) optical design using a dichroic prism (termed X-Cube in this report), characterizing the temperature compensation and response linearity.
- Developing the mechanical, optical and electronics design of the 3 wavelength BAM in a small form factor.
- Developing a preliminary Bill of Materials (BOM) for the 3 wavelength BAM instrument.

The rest of FY08 consisted of securing Phase-II support, although continued development and testing of the BAM sensor continued.

## RESULTS

The BAM-Triad attenuation measurement incorporates a source assembly with a dichroic prism (**Fig. 2**) fed by three separate light-emitting diodes ( $\lambda = 470 \text{ nm}$ ,  $532 \text{ nm}$ , and  $660 \text{ nm}$ ). The dichroic prism is designed to allow transmission of each of the sources via dichroic reflection for the blue and red LEDs and band-pass transmission for the green LED. This is the same technology currently used in LED projection televisions. As a result of this large-volume application, dichroic prisms are now inexpensive (<\$50 in some cases) and available in a variety of sizes and spectral properties. The optical, electronic, and mechanical components are cheap, and the design would lend itself to snap-together assembly. Control electronics will alternate between the different LED sources to provide alternating spectrally discrete outputs. This inexpensive design enables a multi-spectral source with no moving parts.

Under our Phase I base efforts, we developed and tested a bench top optical and electronics configuration for the BAM using a single red (660nm) LED. Results demonstrated that the warm-up characterization, temperature stability, bench top stability, and dynamic range are all comparable or superior to the commercially available WET Labs 660 nm C-Star sensor. Before embarking on testing the 3 wavelength BAM design, we repeated these same analyses using our single wavelength optical and electronics bench top configuration for the blue (470 nm) and green (532 nm) LEDs. Below is a summary of the results for all three wavelength LEDs used.

### *Single wavelength configuration testing*

The single wavelength BAM optical breadboard configuration uses a proprietary WET Labs ECO G2 electronics board set running standard production level ECO firmware. This assembly was exercised through temperature and linearity testing. The temperature correction scheme developed uses a reference detector to compensate for thermal variations of the LED output.

The breadboard was placed in an aluminum can and taken through a 35 to 5 degrees C temperature variation using a temperature controlled water bath. Results using this single LED configuration and

reference correction method showed the total deviation over the 35 to 5 deg C range is ~35, 22, and 23 counts for the red (660nm), green (532nm), and blue (470nm) wavelengths respectively. The uncorrected and corrected (using the reference measurement) variations with temperature in the breadboard tests are plotted in **Fig. 3** for the red LED as an example. At 305.25uV per count, this yields ~11mV, 7mV, and 7mV of total excursion for the red, green and blue wavelengths respectively. The current production goal for a WET Labs C-Star sensor is 20mV, and the upper tolerance limit is 30mV. These results demonstrate that the temperature stability, bench top stability, and dynamic range are all comparable or superior to the commercially available WET Labs C-star sensor.

### *Three wavelength configuration (BAM-Triad)*

The development of the BAM-Triad started with a specified beam measurement length of 5 cm (**Fig. 2**). Three LEDs were selected that have also been previously used in WET Labs' "C-Star" attenuation meter. The red wavelength is 650 nm, the green wavelength is 532nm, and the blue wavelength is 470nm. Each wavelength passes through a 1 mm OD aperture then through a 6mmOD aperture. The light is collimated by a plano-convex lens (10 mm in diameter) with a focal length of 36 mm. The fixturing of LEDs allows independent X, Y, and Z adjustment, allowing for fine tuning to the focal length at the front edge of the 1 mm OD aperture.

Each collimated light path then passes through the dichroic X-Cube prism. BAM-Triad does not use the X-Cube for color combination necessarily but for optical path simplification. At the output of the X-Cube, the light passes through a 50/50 non-polarizing beam splitter (NBS). One-half of the light is directed to a reference detector. The reference detector is used to correct the measurement signal for temperature effects both in the LEDs' outputs and the main detector's response. With half of the light at the output of the NBS, it passes through the 5cm test length. Finally, the remaining light that has not been attenuated within the test volume is passed through a plano-convex lens (10 mm in diameter) with a focal length of 36 mm. The light passes through a 6 mm OD aperture, and is focused on a 1.5 mm OD aperture. Behind the 1.5 mm OD aperture is the signal detector.

A test fixture was constructed from our BAM-Triad design (**Fig. 4**). Note in the CAD model view, the X-Cube is largely oversized. Because of the cost associated with developing an X-Cube with the form factor desired for the BAM-Triad, an X-Cube from the manufacturer (Foreal Spectrum, Inc) was loaned to WET Labs for testing purposes, in this case, one specifically for a rear projection optical engine. The light path only uses a fraction of the glass space. Once an instrument design is completed, an X-Cube of 10 mm x 10 mm x 10 mm will be utilized, which will be provided from Foreal Spectrum, Inc. to meet our specifications.

In the Triad X-Cube configuration, red and blue signals corrected for thermal variations within specification. The thermal compensation test with the green wavelength signal did not sufficiently account for the LED variations to meet our specification (**Fig. 5**). The blue corrected error from 5 to 35 deg C was 73 counts. At 305.25 uV per count, this yields about 22.3mV of total excursion. The green corrected signal error was 150 counts, or about 46mV of total excursion. The red corrected signal error was 55.2 counts, or about 17mV of total excursion. While the green wavelength reference variations did vary in a similar manner to the signal variations, the overall magnitude of the variations were not sufficient to fully compensate for the green LED output changes with temperature. In previous tests using the single wavelength bench top test fixture, the ability to accurately correct for the LED output variations due to thermal changes was very dependant on the alignment of the system optics. In reviewing the results from this initial thermal compensation test, we noted that the reference output made during the green wavelength measurement was significantly lower than expected (~50% of

signal measurement) in comparison to the red and blue reference measurements. The reference measurement is made downstream of the focusing optics (and X-Cube) using a 45 degree beam splitter. Slight misalignments in the focal optics of the green LED system are one suspected cause for the reduced light output as measured by the reference detector. Recall that in the tests using the green LED in the single wavelength bench top fixture, the results showed that the reference measurements closely tracked the green LED signal output with changes in temperature (see above). Thus, we assume that during our initial BAM-Triad test, the green LED suffered from a slight misalignment. These tests are being repeated with an improved focusing scheme for each of the 3 LEDs in the Triad fixture.

With the completion of testing on the BAM-Triad optical test fixture, a design more suitable for an in-situ instrument commenced. The general form factor of WET Labs' SAM and AUV-B sensors allows for both a stand-alone instrument and one that fits into a Webb Research Slocum AUV hull. The design required that the optics not protrude into the flow stream and are protected (**Fig. 6**). The rectangular form allows multiple path lengths of 5 cm up to a maximum 14 cm path length. The AUV-B form factor created the necessity to change the BAM-Triad optical path (**Fig. 7**). The light path was changed from planar to a folded path by utilizing 90° mirrored cubes. By bonding the optical components, the new monolithic "optical engine" not only allows for the optical components to fit within the space constraints but creates a very rugged optical assembly. These two base mechanical and optical designs provide the key groundwork for future Phase-II development.

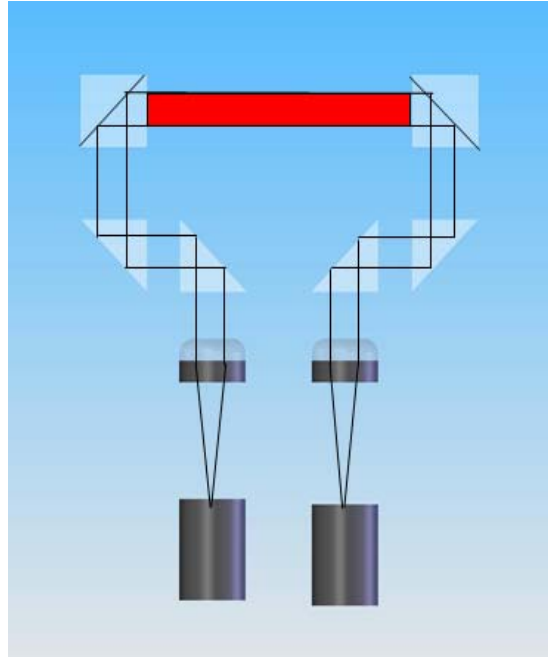
The updated SWAN drifter design for Phase-II incorporating the new BAM design is shown in **Fig. 8**.

## **IMPACT/APPLICATIONS**

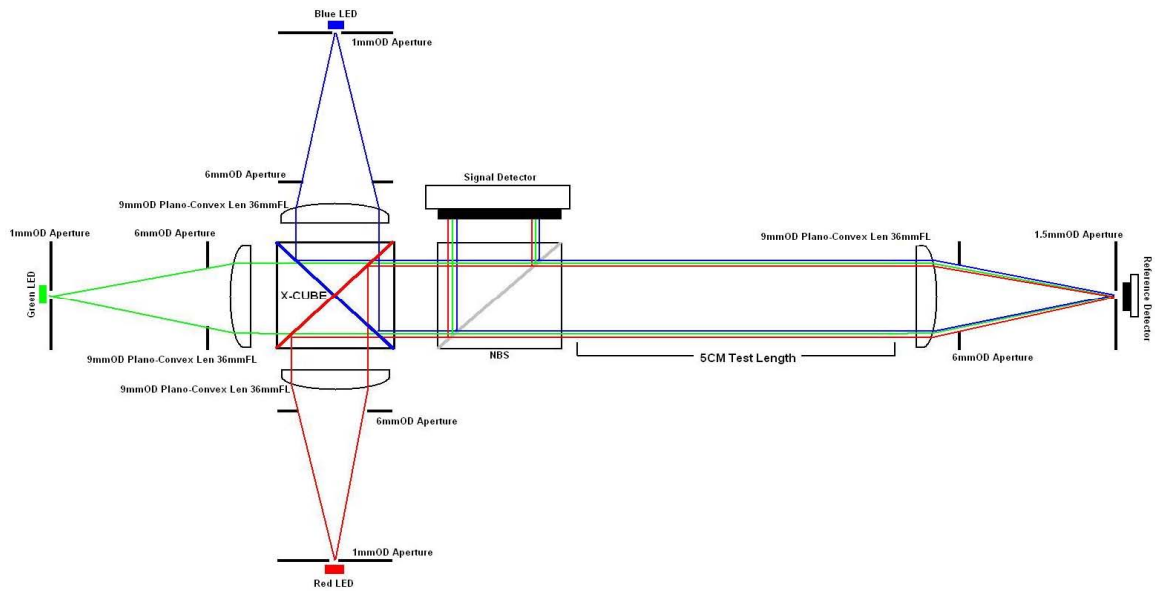
Progress and results represent important steps toward the development of a surfzone optical sensing system measuring  $a$ ,  $b$ ,  $c$ , and  $b_b$  for Naval operations and oceanographic research. Knowledge of the Inherent Optical Properties of water can be used to predict and optimize the performance of a host of Naval operations that rely on divers, cameras, laser imaging systems, and active and passive remote sensing systems. These include mine countermeasures, harbor security operations, debris field mapping, anti-submarine warfare, and search and salvage operations. These measurements are also widely used in environmental monitoring and research applications for determining particle concentration, particle composition, and water clarity.

## **TRANSITIONS**

We expect that our efforts in developing optical sensors for automated deployment platforms and our success in integrating these sensors on such platforms will lead to transition of these optical sensors into operational tools for the fleet and the oceanographic research community in the future. Parent sensors to the sensors under development in this work are currently being used on automated platforms in Naval mine countermeasure exercises such as RIMPAC and in ONR research initiatives such as OASIS and RADYO. Slocum gliders equipped with these sensors are used in academic research (Rutgers University and North Carolina University), in recently delivered NRL slocum gliders, and in recently ordered Naval Oceanographic Office gliders.

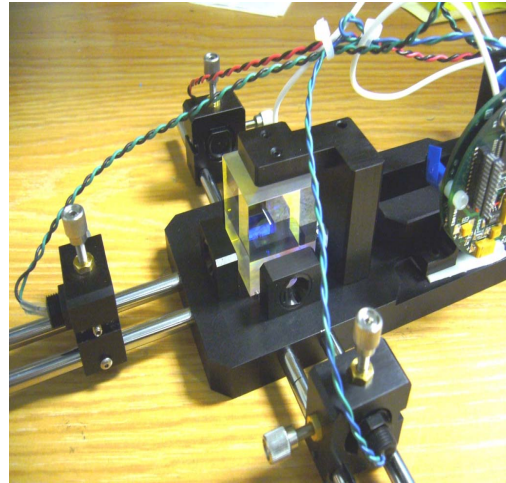
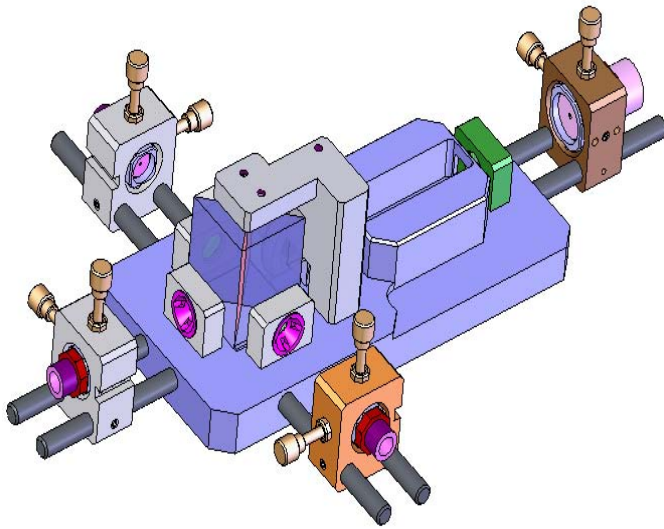
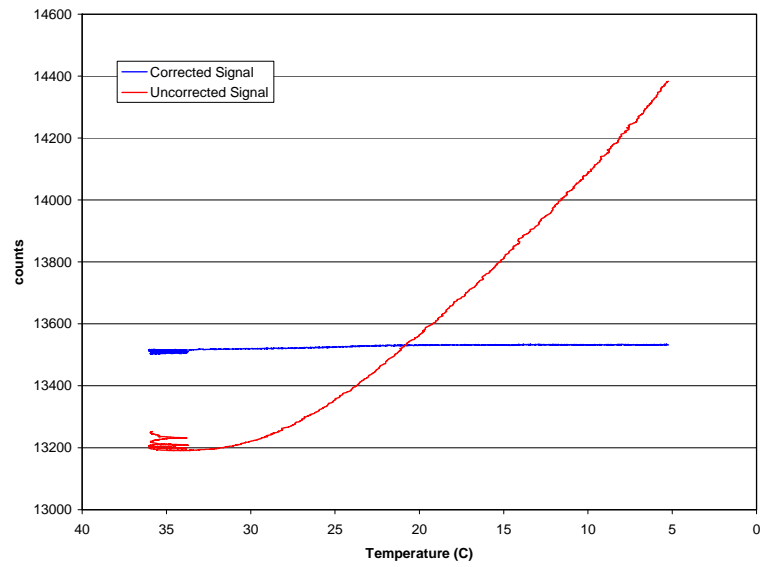


***Fig. 1. General optical lavout for BAM.***



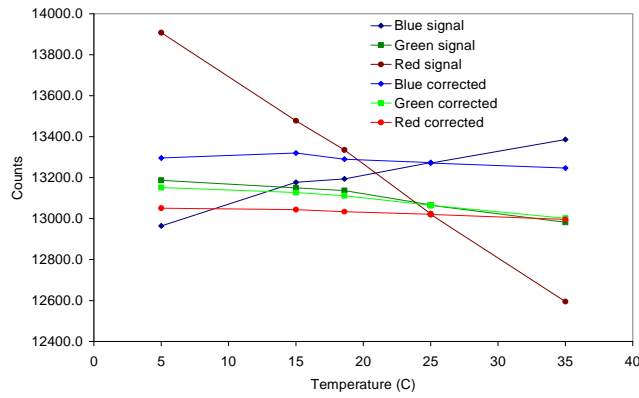
***Fig. 2. Optical Layout of BAM-Triad***

**Figure 3. Signal variation (uncorrected and corrected using reference measurement) of the red LED single wavelength BAM optical breadboard as a function of ambient temperature.**



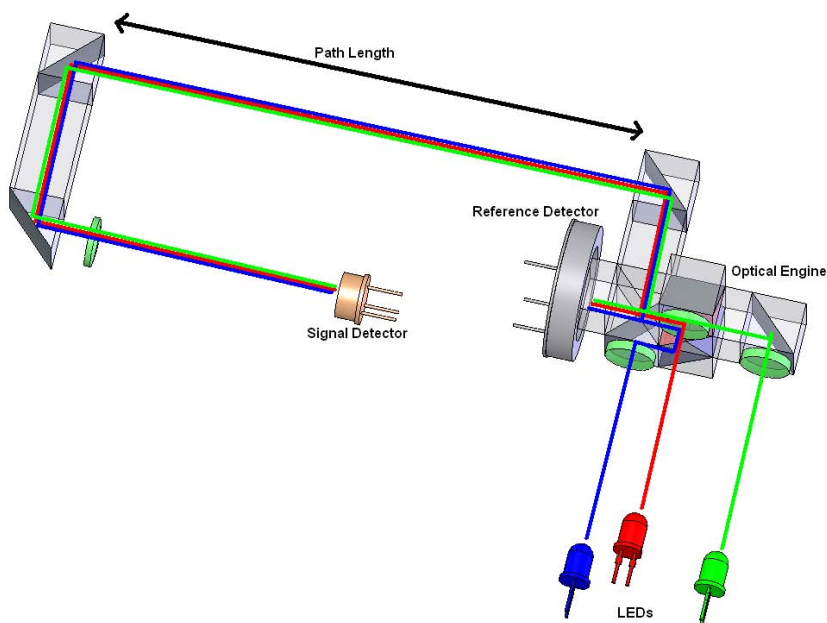
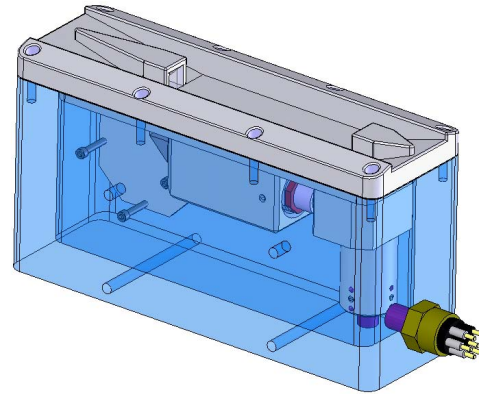
**Figure 4. 3D CAD Model (A) and bench top implementation (B) of BAM-Triad Test fixture.**



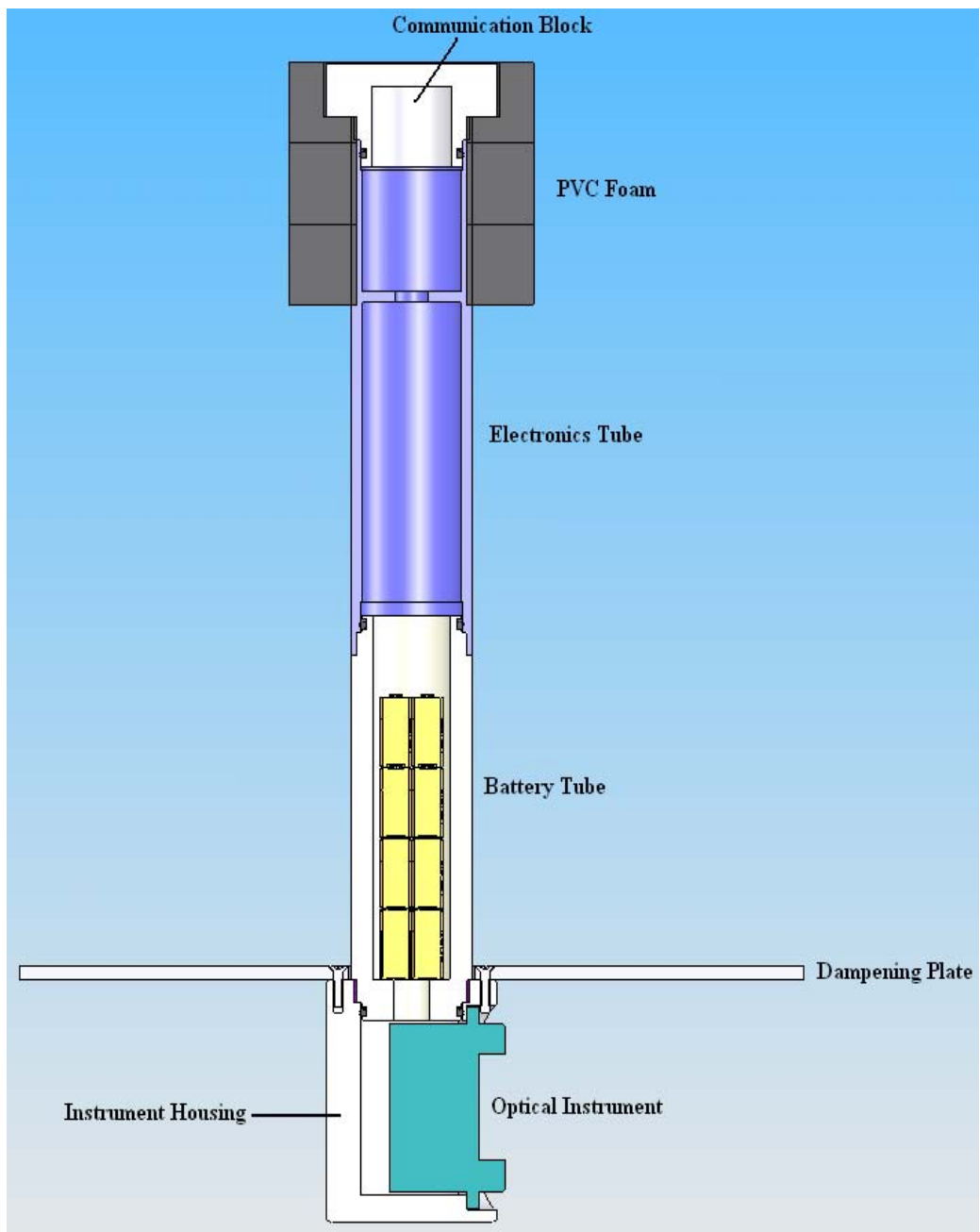


**Figure 5. Signal variation relative to temperature (raw and corrected using reference measurement) of the red, green, and blue LED wavelengths using the BAM-Triad optical breadboard fixture.**

**Figure 6. A 3D CAD model of a 14 cm pathlength BAM in an AUV-B form factor with pressure housing.**



**Figure 7. CAD model of BAM-Triad optical path and components adapted to form factor of the AUV-B and SAM.**



*Fig. 8. SWAN platform design.*

## RELATED PROJECTS

Miniaturizing and integrating sensing technologies for use on a host of new autonomous sampling platforms has been a major focus for WET Labs for the past few years. Several R/R&D efforts ongoing and in the recent past reflect this focus:

1. WET Labs is working in partnership with several collaborators to develop moored optical and chemical profilers for 4-D characterization of coastal waters (URI, NOPP).
2. WET Labs is working in partnership with researchers in the development of miniature attenuation sensors using a conventional transmission configuration. These sensors are to be incorporated on next generation profiling drifters (LBN Labs and SIO, ONR contract).
3. WET Labs is working in partnership with researchers to develop next generation biooptical tools for integration on Erikson Gliders (U. Maine, U. Washington, NOPP).
4. WET Labs is working in partnership with researchers to develop next generation optical tools for application in long-term moorings (UCSB, ONR contract).
5. WET Labs is funded by NASA to develop and implement miniature optical sensors for deployment on PALACE floats (Boss and Zaneveld, PIs).
6. WET Labs is funded by NASA to develop a towed, integrated optical profiling system for synoptic remote sensing validation work through a Phase-II SBIR (Twardowski, PI).
7. WET Labs is funded by ONR to develop a compact, robust, hydrodynamic attenuationmeter using a novel technique compatible with a small form factor (Twardowski, PI).
8. WET Labs is funded by NASA to develop an in-situ biogeochemical sensor using excitation-emission matrix (EEM) fluorometry through a Phase-II SBIR (Moore, PI).
9. WET Labs is funded by NASA to develop an optical sensor for making robust analytical determinations of biogeochemical parameters such as TSM and POC (Twardowski, PI).

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